Models of the Nucleus: Incompatible Things, Compatible Processes

William A. Penn

Nuclear models are incompatible in their thing-terms: terms that refer to static entities like objects, structures, and substances. Specifically, the two most prevalent models—the liquid drop and shell models—treat the nucleus, its internal structure, and the component nucleons as entities that contradict each other's properties. These differences allow these two models to describe and explain different nuclear experiments: fission and scattering in the liquid drop model, and single-nucleon excitation and nuclear decay in the shell model. However, prima facie, these differences also suggest that these models are incompatible in their ontology. However, by taking seriously the experimental methods by which these models are constructed and the calculational tools these models provide for interpreting experimental outcomes, I construct a new form of realism about these models that renders them ontologically compatible. Namely, I argue that nuclear models are consistent in the dynamic entities to which they refer. I therefore advocate a pure process realism with respect to nuclear models. Critical to this process realism is the recognition that the processes referred to within nuclear models are essential parts of the observation acts that form nuclear experiments. In particular, because the dynamics within the nucleus must always be a continuous intermediary of our experimental interventions and the receptions of signals from the system, these dynamics are essential dynamic parts of nuclear experiments. We are therefore licensed in inferring these dynamic parts on the basis of experimental practice alone. In contrast, the thing terms reified by the thing realist in these models require additional inferences, the premises of which cannot be supported on the basis of experiment alone. Thus, inferences to processes are experimentally supportable, whereas inferences to things are dubious at best.

Keywords: Nuclear Physics, Process, Realism, Scientific Metaphysics, Models and Modeling

[1]: Introduction

Nuclear models are incompatible in their thing-terms: terms that refer to static entities like objects, structures, and substances (Boniolo et. al. 2002, Teller 2004, Morrison 2011, Portides 2011). Specifically, the two most prevalent models—the liquid drop and shell models—treat the nucleus, its internal structure, and the component nucleons as entities with contradictory properties. These differences allow these two models to describe and explain different nuclear phenomena: fission and neutron-scattering in the liquid drop model, and single-nucleon excitation and nuclear decay in the shell model. However, prima facie, these differences also suggest that these models are incompatible in their ontology. Indeed, by maintaining an adherence to standard static ontologies of objects, structures, and substances, henceforth "thing realism,"[1] this incompatibility is irresolvable. Any success of their explanations comes not from the entities, properties, and structures they posit but from somewhere else.

This presents two problems. First, there is an ontological problem with this incompatibility: to what are we referring to when we use the term "the nucleus"? Second, there is an explanatory problem: how can we reasonably use one set of features of the nucleus to explain successfully if those features are incompatible with equally explanatory features of a different model? The explanatory problem is built on top of the ontological problem. The ontological problem suggests that the explanations offered by, e.g., the liquid drop model are reliant on entities that *cannot* exist, meaning that the explanations are akin to explaining the functioning of a computer with square circles. In other words, the incompatibility of these

---

[1] Examples of thing realism abound. See Wiggns (2016a, b, c) for an example of a mixed ontology that treats substance as the continuant of an active principle.

models is more than the result of attributing different features to a single system: each model denies the possibility of the (thing) ontology offered by the other.

However, this is only a problem with a thing-interpretation of these models. By taking seriously the experimental methods by which these models are constructed and the calculational tools these models provide for interpreting experimental outcomes, I construct a new form of realism about these models that renders them ontologically compatible. Namely, I argue that nuclear models are consistent in the dynamic entities to which they refer: the interactions of nucleons, the excitations of the aggregate whole and its parts, the decay processes the system undergoes, and, in general, the processes of the nuclear system. Here "process" is a primitive term used to refer to the sort of entity exemplified by motions, interactions, excitations, growths, decays, etc.[2] Similar to recent work by other authors in the philosophy of science (Dupre 2010, 2018; Earley 2003, 2008; Kaiser 2018; Guay and Pradeu (forthcoming); Guay and Sartenear 2018), I therefore advocate a pure process realism with respect to nuclear models: we should reify these dynamics without reifying the objects, structures, and static properties that are demonstrably incompatible. By doing so, I argue that both the liquid drop and shell models are fully compatible and successfully explanatory. The nucleus, therefore, is no more than a collection of processes.[3]

---

[2] I use the word "process" in much the same way as Seibt (1990, 2004, 2005, 2018) uses the word "dynamics." Importantly, it is a primitive term and cannot be defined independently. However, as I have suggested here, it is possible to build a working definition of process from various paradigmatic examples. Motions, interactions, decays, excitations, growths, etc. are all paradigmatic processes. Penn ("Introduction to Process Realism" manuscript) provides a brief explanation of these paradigms with the interest of building a working concept for the primitive process. See also Pemberton (2018), Griesemer (2018), Love (2018), and Chen (2018) for more on constructing a working definition of process within scientific theory (specifically biology).

[3] Similar claims have been made about other systems. For example, Penn ("The Processes of the Candle Flame" manuscript) and Penn ("Reimagining Perrin's Robustness Argument" manuscript), has been argued that thermal systems like the candle flame are explained and investigated solely with processes, and that any apparent reference to or inference of things is better described historically and physically as a reference/inference of processes. Penn "Are we Justified in Inferring the Existence of Dark Matter?" manuscript) argues for a similar conclusion about

Critical to this process realism is the recognition that the processes referred to within nuclear models are essential parts of the observational acts that form nuclear experiments. In particular, because the dynamics within the nucleus must always be a continuous intermediary of our experimental interventions and the reception of signals from the system, these dynamics are essential dynamic parts of nuclear experiments. We are therefore licensed in inferring these dynamic parts on the basis of experimental practice alone. In contrast, the thing terms reified by the thing realist in these models require additional inferences, the premises of which cannot be supported on the basis of experiment alone. The essential premise of these additional inferences is one of two options (a) that all dynamics (metaphysically) require static things to underlie them, [4] or (b) that the existence of stability in an experimental system necessitates something static and unchanging within the system.[5] These premises are question-begging if deductively supported, and insufficient if inductively supported. Thus, inferences to processes are experimentally supportable, whereas inferences to things are dubious at best.[6] Process realism is therefore superior to thing realism in the context of nuclear models because it:

(1) establishes cross-model consistency,

(2) accords with experimental practice and explanations, and

---

cosmological material entities. Parr et. al. (2005) and Bader (1999, 2008) problematize the molecular system in a similar way. Hattema (2007) describes some of the problems in the history of molecular modeling, e.g., the Heitler and London (1927) and the Hund (1927) models of the molecule. Earley (2003, 2008) argues explicitly for a "process structural realism" about the molecule that is quite similar to what I articulate here. The largest difference is that Earley is willing to reify structures within the molecule, while I take this as impossible given that structures in the nucleus are a part of the incompatibility of nuclear models.

[4] This is a claim that dates back to Aristotle. See *Physics* 190a31-b9. Penn ("Processes Underlie Processes" manuscript) shows that this claim begs the question. Seibt (1990) also criticizes this premise extensively.

[5] Penn ("Processes Underlie Processes" manuscript) shows that this argument cannot rule out that processes, not things, underlie processes and stabilities. Penn ("The Processes of the Candle Flame" manuscript) provides an example of how we explain stabilities in terms of processes. Penn ("Reimagining Perrin's Robustness Argument" manuscript) provides an in-depth example of this argument, and shows that the argument actually rules in favor of process undeliers.

[6] This has been argued extensively in Penn ("Processes Underlie Processes" manuscript).

(3) is epistemically modest.

We begin in section 2 with a brief introduction to the liquid drop and the shell models of the nucleus. In addition to the normal exegesis, I will also show how these models are ontologically incompatible on any form of thing realism (object, structural, substantial, bundle-theoretic, etc.). In section 3, we turn to reinterpreting the material and formal features of the nucleus in terms of dynamic entities (motions, excitations, etc.). In discussing the formal and material features meant to support the haeccity of the nucleus, I offer the standard process realist arguments that these features are no more than real dynamics with the added knowledge that they cannot be reinterpreted as things in any sense. I then show that the explanations of the nuclear models rest on these dynamics, and that these dynamics are compatible. Their compatibility is the result of both models acknowledging the existence of all processes, but only using a subset of these processes in order to explain the salient behaviors of the nucleus.

[2]: Many Models, Divergent Things

There are many models of nuclear systems corresponding to many phenomena.[7] Liquid drop models, developed in the 1930's, are still used to model the fission of a nucleus. Shell models, similar to molecular and atomic orbital models, are used to model nuclear line spectra, and to a lesser extent the stability of the nucleus. Lattice models are used to understand nucleus formation and structural binding stabilities. For our purposes here, we will consider only liquid drop and shell models. Considering these two will be quite sufficient to establish that no

[7] See Cook (2006) for an overview of the various types. One type not discussed by Cook, more recently developed, is the so-called unified lattice model. See Caurier et. al. (2005). It is worth noting that this model is not a unification of the liquid drop and shell models. The hope is that the model will be able to unify explanations of nuclear decay and of scattering experiments, but the model cannot explain fission. It is still unclear that the model can explain spectral emission.

robustness argument—an argument that terms in these models refer to real things in virtue of their appearance and similarity in both (and more) models[8]—can be made for the reality of things in the nucleus, or for the nucleus qua thing itself. Insofar as "the nucleus," "nucleons," "Energy structure," etc. appear as identical terms in models of nuclear systems meant to refer to a static thing, the terms are wildly divergent in meaning. The models therefore contain no robust thing-terms.

[2.1]: The Liquid Drop Model

The liquid-drop model treats the nucleus as a drop of incompressible fluid of similar shape and structure to a drop of water. This analogy facilitates a highly accurate account of the nuclear binding energy and of how nucleons act together to produce collective, nucleus-wide motions such as fission. The model achieved its success primarily through this description of fission given by Meitner and Frisch (1939).[9]

In a drop of liquid, molecules will meaningfully interact only with their nearest-neighbors. For example, water molecules in a drop of water will electrostatically repel and attract each other and undergo collisions brought about by the momenta and thermodynamic vibrations of the molecules. Each of these interactions is between exactly two molecules, and the interactions are only significant when these molecules are sufficiently close to each other. The liquid-drop model of the nucleus imports near-exactly this reasoning to nucleon-nucleon interactions. The model assumes that there is a strong attractive potential, built from pairwise

[8] Penn ("Processes Underlie Processes" manuscript) and Penn ("Reimagining Perrin's Argument" manuscript) offer in depth discussions of robustness arguments in general and in a particular historical case study respectively. Both are written in the context of a discussion of process realism and thing realism.

[9] For a fully detailed explanation of the history of this model, see Stuewer (1994). See Gamow (1929) for the first liquid-drop model. See Cook (2006, ch. 4) for a detailed introduction to the liquid-drop model.

interactions between nearest-neighbor nucleons, binding the nucleus together, as well as electrostatic repulsion between nearest-neighbor nucleons that prevents collapse.

This assumption entails a difference in binding energy between particles at the surface and particles within the volume of the liquid-drop. Particles at the surface will always have fewer neighbors than particles within the volume. Thus, particles at the surface of the drop will be much more weakly bound than particles in the interior of the drop. This means that the binding energy of the liquid-drop is expressed by the following proportionality (k_1 and k_2 are real constants, mere proportions):

$$(Eq.\ 1)\ E_{binding} \approx k_1(number\ of\ particles) - k_2(number\ of\ particles)^{2/3}$$

As the number of particles increases, the first term—the volume term—begins to dominate the second term—the surface term. Thus larger drops are less stable, since they have lower binding energy.[10] Following this analogy, the nucleus

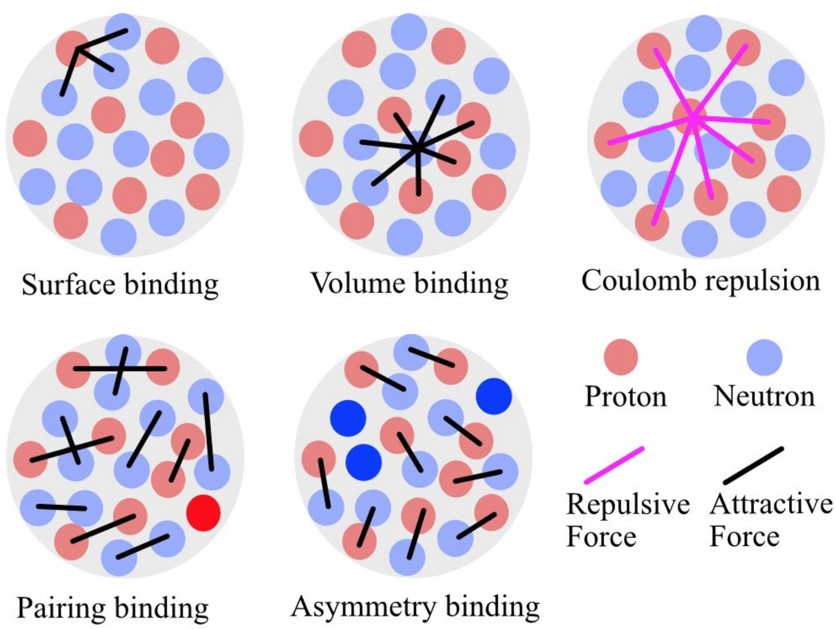


Figure 1: The nearest-neighbor interactions described by the liquid-drop model. Pairing and Asymmetry binding forces are empirically, not theoretically, motivated.

[10] Note that by convention, binding energy is considered large when it is a large negative number.

therefore exhibits similar behavior to that given by equation 1.

Additional pairwise interactions are added to this nuclear model to provide further accuracy to the theoretically predicted binding energy (figure 1). First, one recognizes that protons will repel each other. Therefore an additional repulsive term is added to the proportionality of equation 1. Second, empirically motivated terms are added recognizing that nuclei with an even number of nucleons have higher binding energy (pairing), and recognizing that nuclei with an equal number of neutrons and protons tend to have higher binding energy (asymmetry). These are collected in the Weizsäcker mass-energy equation:

$$(Eq.\ 2)\ BE(Z,\ A) = k_1A + k_2A^{2/3} + k_3Z(Z-1) + k_4\frac{(A-2Z)^2}{A} + k_5\frac{1}{A^{1/2}} + shell\ correction\ terms$$

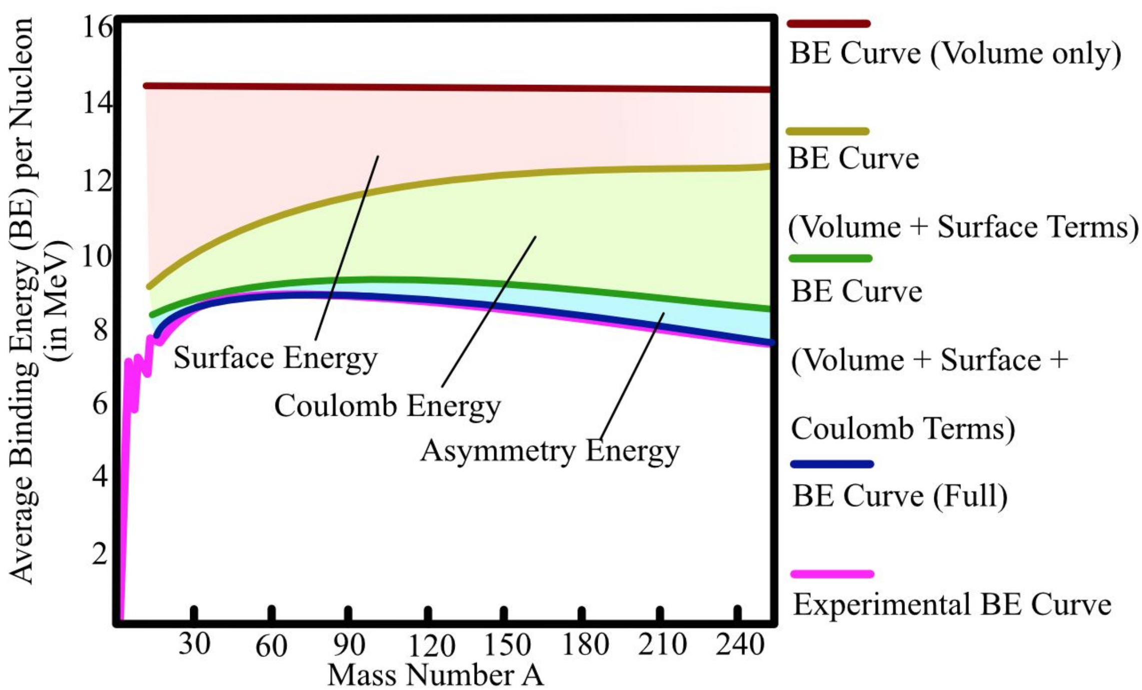


Figure 2: A depiction of the relative effects of each interaction type on the accuracy of the predicted binding energy curve. The energy of each interaction type is shown as the difference between curves.

Figure 2 shows the relative effects of each term in moving the theoretical binding energy curve closer to the observed binding energy curve.[11]

With all of these terms accounted for, the liquid-drop model is able to explain vibrational and oscillatory resonances of the whole nucleus. Any disturbance in the nucleus as a whole will be the result of many interactions between neighboring nucleons. For example, if a nucleus is struck by a low-energy bombarding neutron, this neutron's energy will distribute throughout the nucleus through the nearest-neighbor interactions depicted in figure 1. Impacted nucleons will similarly interact, causing the nucleus as a whole to enter a higher energy state. The nucleus will redistribute the energy of the bombarding neutron among its nucleons until this energy is released through nucleon emission or fission.

[2.2]: The Shell Model

While the liquid-drop model is concerned with analyzing the behavior of collections of particles, the shell model considers the behavior of an individual nucleon. The model seeks to explain only the behavior of this individual nucleon and treats all other nucleons as equivalent to an external Fermi field to which this nucleon couples. The nucleon is therefore treated as if it were part of a diffuse Fermi gas, much like the electrons bound in an atom. This facilitates a description of how an individual nucleon can occupy and transition between energy states within the nucleus. This in turn allows the model to explain the special stability of nuclei with certain numbers of nucleons: the so-called magic numbers.[12]

---

[11] See Weizsäcker (1935) for the full mathematical treatment of these terms.

[12] The first shell model is presented by Mayer and jensen (1955). For a modern introduction to the model, see Cook (2006, ch. 2).

Two facts are suggestive of nuclear energy shell-structure. First, an individual nucleon will not collide with other nucleons very frequently. Were such collisions to occur, nuclei would be far less stable in various decay processes than observational data suggests. Second, for an individual nucleon, the forces acting on it from the other nucleons can be amalgamated into a single quantum potential well to which the nucleon couples—a Fermi field. Thus, the nucleon will enter quantized energy levels, the structure of which will depend on the shape of the potential well imposed on the individual nucleon. These facts entail that nucleons occupy non-coinciding trajectories within the nucleus. Given that nucleons experience strong attractive forces which would otherwise bring them into collisions, this in turn suggests that nucleon trajectories are kept apart by something like the Pauli-exclusion principle. In analogy with the case of electron orbits in an atom, nucleons are unable to occupy the same trajectories, instead occupying discrete trajectories quantized by the total angular momentum and energy of the nucleon occupying that trajectory.

The applicability of the Pauli exclusion principle for nucleons facilitates a direct comparison of nuclear structure to atomic structure: the nucleus can be treated like an electron cloud in an atom. Electrons moving in an atom move in orbits—orbits that are separated from each other by Pauli exclusion—defined by a central, attractive potential well. Each electron occupies the lowest-energy orbital that is not already filled by another electron, and orbits are quantized in terms of the net energy, angular momentum, and spin of the occupying electron. Similarly, nucleons in the shell model occupy energy levels—"orbits" or "energy shells"—which are defined by something like the harmonic oscillator potential well. The energy levels associated with coupling the nucleon to such a harmonic potential well are depicted in figure 3 (left hand lines). Two nucleons, like electrons in the atom, are incapable of occupying the same energy level in virtue of Pauli exclusion. Finally, having defined nucleon "orbits," one introduces a spin-orbit coupling for the orbiting nucleon. This splits the energy level into sublevels defined by the total angular momentum of the nucleon, as depicted in figure 3 (right hand lines). Just like electrons in an atom, nucleons will occupy the lowest available energy

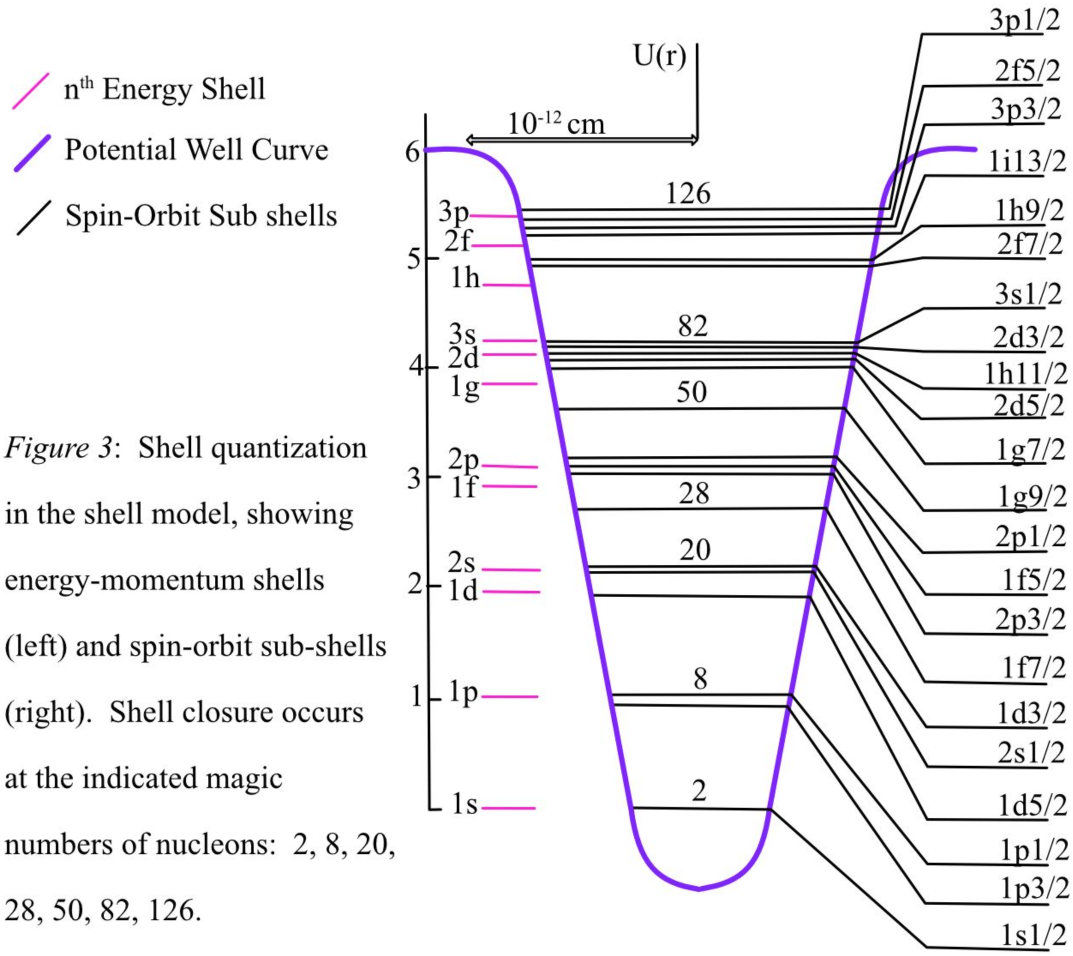


Figure 3: Shell quantization in the shell model, showing energy-momentum shells (left) and spin-orbit sub-shells (right). Shell closure occurs at the indicated magic numbers of nucleons: 2, 8, 20, 28, 50, 82, 126.

level that is not already occupied by another nucleon, and nucleons will transition between two levels only when individually excited with the discrete energy corresponding to the difference in energy between the two levels.

This provides the basis for explaining the magic numbers. Atoms with filled energy shells exhibit much greater stability than atoms with open energy shells, called shell closure. This is why noble gas elements like Helium and Neon are far less reactive than elements like those in the alkali group, e.g., Lithium and Sodium. Helium and Neon have "magic numbers" of electrons—2 and 10—which correspond to the number of electrons needed to fill the lowest energy levels. Similarly, nuclei which fill all the subshells in a given energy shell will experience shell closure, and be much more stable. Shell closure occurs when a nucleus has 2, 8, 20, etc. nucleons of either type.

[2.3]: Incompatibility

We now ask: are these two models describing the same thing? The answer is that they are not. The nucleus of the liquid drop model is quite different from that of the shell model. The two models of "the nucleus" describe the nucleus as having a different shape, different internal structure (e.g., definable spatial relations between nucleons), different spatial extent and density, and different analogous material constitution. This is summarized in table 1.

Feature of the nucleus:	Liquid-drop Model Claims:	Shell Model Claims:	Experimental Results Support:
Entity Claim:	The nucleus is a liquid-drop	The nucleus is a Fermi gas	neither
Presence of internal structure:	There is no internal structure	There is internal structure	both
Shape of the nucleus:	Roughly spherical, varying directly with nucleon number	Roughly spherical, not varying directly with nucleon number	Liquid-drop

Density of the nucleus:	Constant, with a sharp drop at the nuclear radius	Varying, with a gradual drop at the nuclear radius	Shell
Radius of the nucleus:	Proportional to $A^{1/3}$	Proportional to occupation numbers of energy shells, not $A^{1/3}$	Liquid-drop

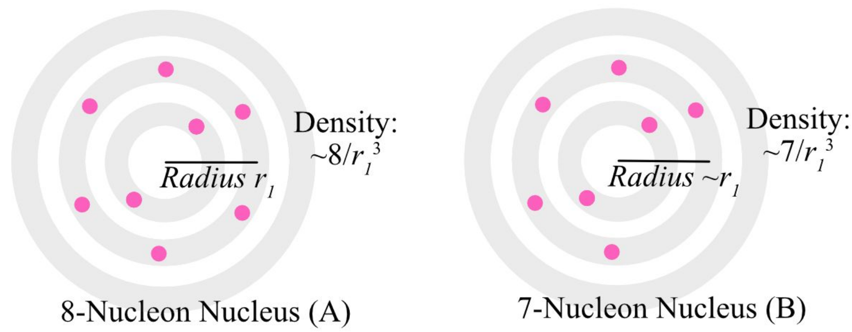
Table 1: A comparison of properties and thing-claims made by the liquid drop and shell models.

First, the liquid-drop and shell models directly contradict each other on the presence of internal nuclear structure. The liquid-drop model admits only a nuclear surface and interior. In contrast, shell models predicts energy shells and subshells, and therefore admit rich internal substructure. Thus the liquid-drop model depicts a nucleus with *no* internal structure, and the shell model depicts a nucleus with *much* internal structure.

The two models also conflict over the size and shape of the nucleus. The liquid-drop predicts an approximately spherical shape for the nucleus resulting from nearest-neighbor attractive interactions between the nucleons. This in turn means that the liquid-drop predicts a sharp drop in nucleon density as one approaches the boundary of the nucleus. There are few-to-no nucleons that exist outside of the nuclear radius. The nucleus, according to the liquid-drop model, has a definite shape and size related to the number of nucleons A; the nucleus is a spheroid of radius proportional to $A^{1/3}$.

In contrast, the shell model predicts that the size and shape of the nucleus depends on the shape and closure of energy shells. This is because nuclear structure in the shell model is almost entirely dependent on the texture of these shells. The nuclear radius will therefore depend on occupation number, not $A^{1/3}$. In addition, the density of nucleons will vary radically between nuclei with magic numbers of nucleons and nuclei without magic numbers of nuclei, again because energy shell structure determines nuclear structure. These features are depicted schematically in figure 4.

Finally, the energy shell structure of the nucleus also entails that nuclear density varies continuously with increasing radius. Rather than a constant density as in the liquid-drop model, the shell model predicts that the tendency of energy shells to spatially separate will cause nucleon density to be inconstant, especially in nuclei with open energy shells.



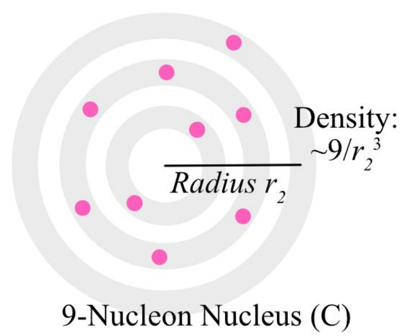


Figure 4: A representation of nuclear density and radius as related to nucleon number. Large differences in both properties are observed between A and C and B and C.

Empirical data do not strictly rule in favor of either model. Rather, both models experience some success in their explanations, and failure in others. The liquid-drop model successfully explains the nuclear radius but not the nuclear density. Fission experiments and neutron bombardment indicate that there is little internal shell structure in the nucleus, supporting the liquid-drop, while scattering experiments and observations of radioactive decay suggest the rich internal structure of the shell model. The models are therefore directly contradictory in a thing ontology, with no apparent way of adjudicating between them. It is no wonder, then, that many authors advocate not only that these models are incompatible, but that we should remain silent on, or else eliminate, thing realist intuitions about the nucleus on the basis of these models (Boniolo et. al. 2002; Teller 2004; Morrison 2011; Portides 2011).[13]

[3]: The Features of the Nucleus are Processes

The liquid drop and shell models are contradictory in their thing terms. Therefore, these thing terms cannot be robust. However, Penn ("Processes Underlie Processes" manuscript) has argued that this is not special. Indeed, we expect that processes are robust where things are not. To see this in the nuclear case, we return to our list of features of the nucleus. These are:

Type Features:	Formal Features	Material Features	Productive Features
Token Features:	-The shape of the nucleus -The internal energy spectrum structure -The radius of the nucleus -The density of the nucleus	-The composition of the nucleus in terms of protons and neutrons. -The composition of decay products produced by nuclear radioactive decay.	-The production of line spectra -Decay product production -Fission -Fusion

Table 2: A list of formal, material, and productive features of the nucleus to be explained.

Importantly, the features of the nucleus that are of most interest are the formal and productive features. These are, at minimum, the features of the nuclear system that models of the nucleus are supposed to explain. We saw this in section 2: the liquid drop model can successfully

[13] Cook (2006) also remarks that the models make inconsistent claims. See also Bohr and Mottelson (1969) for an in-depth, historical account of the tension between these models.

explain the shape and size of the nucleus, and the shell model can successfully explain its internal energy structure.

However, there is an important distinction we must draw: the formal features are not, strictly speaking, the explananda of nuclear models. The liquid drop and shell models are not used in experimental settings, both historical and contemporary, to explain these formal features. Rather, they are used to explain the processual features of the nuclear system: fission, radioactive decay, spectral emission, neutron capture and scattering, etc. These are the phenomena that are actually modeled and occur in experimental settings. The formal features of the nuclear system are therefore explananda only insofar as we might already have thing-realist intuitions.

Moreover, I have already shown how the formal features of the nucleus according to the two models are incompatible. Therefore, these formal features cannot be explanans either. Rather, I show below that the formal features of the nucleus are placeholder terms for collections of processes, useful only for their pragmatic role in describing the evolution and dynamics of interest in the nuclear system. Importantly, this is not an a priori argument, but rather follows simply from the facts of the models and their history. The models were designed to explain dynamics, and use dynamics to do this explaining. This is the explanatory defeat of things: processes do all of the explaining in these models, and are the entities being explained.

In turn, the material features are offered as the thing-realist's hope of an explanans independent of these formal features. Surely, the argument goes, the material composition of the nucleus plays a role in explaining nuclear phenomena simply because nucleons are the bearers of properties and vehicles of processes in the nucleus. As I will articulate, this argument, just like the underlier arguments rejected in Penn ("Processes Underlie Processes" manuscript), fails because it does not rule out that the nucleons are themselves processes or collections thereof.

However, just like with the formal features, the incompatibility of nuclear models on thing-realist interpretations makes it difficult to see how appeal to thing-nucleons is meant to resolve anything. Given that these nucleons have to be fit into incompatible models as explanatory elements, they will inevitably inherit that incompatibility. For example, if nucleons are meant to both occupy discrete energy shells and not occupy these shells, the nucleons themselves will need to have a property[14] "energy within the nuclear system" that is one value in the liquid drop model and another in the shell model.

This means that things are defeated ontologically as well. No thing term may be reified in both of these models on pain of contradiction, and no thing term may be thought to explain in either of these models. Instead, as I show below, all we need are processes. Processes are explanans, explananda, and ontological ground in both models. Moreover, the processes of each model are compatible with each other. I turn now to a re-analysis of the features of the nuclear system, in order to show this.

[3.1]: Formal Features of the Nucleus: Balanced Dynamics

For the sake of simplicity, let us consider only two formal features of the nucleus: the shape of the nucleus and the internal structure of its energy spectrum. We use the liquid drop model to explain the former, whereas we use the shell model to explain the latter. Moreover, the two models provide correct explanations for their respective features of the nuclear system, but

[14] Note that the property need not be basic or fundamental, but will need to be constructible in order for the thing realist to reify the nucleon.

fail to explain the other feature. Naïvely, this suggests that, even independently of the incompatibility of the thing interpretation of the two models, these two models cannot find common ground. As we will see, the processes used to explain these two features are indeed common ground between the models: the models do not contradict in their process realist interpretation.

[3.1.1]: The Shape of the Nucleus

The shape of the nucleus is explained by the liquid drop model. This explanation is simple: the shape of the nucleus is the result of all of the inter-nucleon interactions (as catalogued by the Weizsäcker mass-energy equation) being balanced against each other to minimize the total energy of the nuclear system. In other words, the electromagnetic and chromodynamic interactions, both represented as simple modifiers on the strength of each term in the Weizsäcker mass-energy equation, counteract each other to bring about a stable configuration of the system. In other words, the shape of the nucleus is not some static feature of the nucleus, but is rather the result of a balance of multiple dynamics within the system. This matches other discussions of structures in chemistry (Earley 2003, 2008) and physics (Finkelstein 1996, 2003; Penn "The Processes of the Candle Flame" manuscript)

However, it is far more interesting to note how the shape of the nucleus plays a role in the explanation of fission. Data on neutron bombardment of nuclei puzzled physicists in the 1930's (Stuewer 1994). The best theories of the nucleus predicted that for low-energy neutrons, neutron capture should be as likely as scattering from the nucleus. However, experimental results showed that neutron capture was much more likely. In addition, data showed that for each element, neutrons with certain energies were absorbed at higher rates. This too disagreed with the current theories of the nucleus.[15]

Bohr's compound nucleus provided the solution to these problems. Bohr analyzed the process of neutron bombardment into several distinct stages. First, an incident neutron impacts the nucleus. Second, the nucleus absorbs the neutron, and the neutron's energy is distributed among the nucleons in nearest-neighbor interactions. Then, if enough energy is collected into a single nucleon, that nucleon is ejected from the nucleus.[16] However, if there is not enough energy to eject a single nucleon, the nucleus captures the incident neutron. The energy required to eject neutrons from a nucleus of a given element depends upon the particular binding energy of that nucleus. Thus, only neutrons with particular energies will be able to "scatter" by being ejected from the nucleus: a compound nucleus with captured neutron is more likely to form if the energy of the incident neutron is enough to excite the nucleus into the next highest energy level of the nucleus as a whole. This effect, which Bohr (1936, 344) called "resonance excitation" explains why neutron capture is more likely than scattering, and why certain neutron energies produce peak capture or peak scattering. Here, resonance is taken literally, unlike in discussions of molecular resonance. Bohr is literally describing the nucleus as resonating, i.e., vibrating with harmonics in tune with the incident energy of the bombarding neutron. When resonant, the nucleus enters a standing wave oscillation pattern. It is these standing wave oscillation patterns that constitute the energy levels of the nuclear system, just like the standing waves of a string on a cello.

[15] See Pais (1981, 336-337) for more on this historical difficulty.

[16] See Bohr (1937, 163) for this exact account, with explicit reference to both processes and stages (intermediate states) of a process. See also Bohr (1936).

This explanation was later extended to include the emission of larger clusters of nucleons by Meitner and Frisch (1939).[17] Instead of emitting only a single nucleon when in an excited state, Meitner and Frisch proposed that oscillations of a compound nucleus split that nucleus into two smaller nuclei through the same process as Bohr describes. This is depicted schematically below, in figure 5.

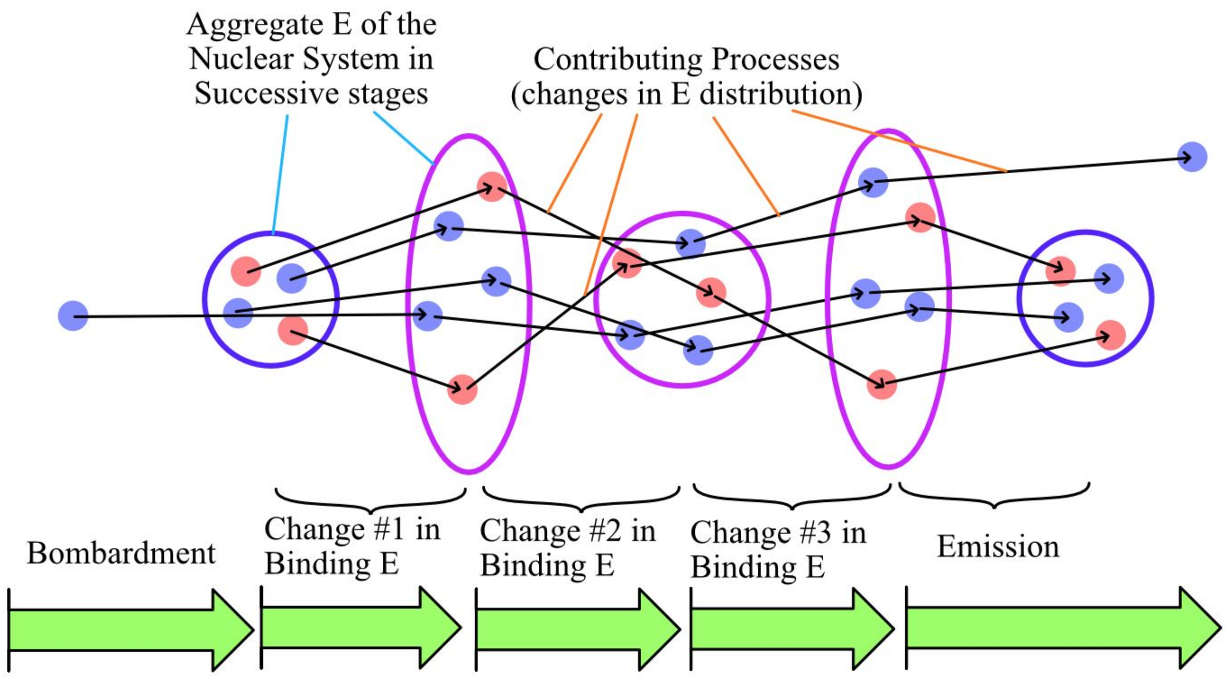


Figure 5: A schematic of the identifiable, token processes involved in a token scattering event as described by the liquid drop model.

These oscillations of the nuclear system are oscillations in the shape of the nucleus. However, these oscillations are the result of a disturbance of the balance of strong and electromagnetic interactions. When we bombard the nucleus with a neutron (our intervention), this bombardment produces a change in the system: the emission of two or more fission

[17] See Stuewer (1994, 107-116) for a full account of the historical development of the liquid-drop account of fission offered by Meitner and Frisch. See also Frisch (1939) and Meitner (1936).

products. We observe that the fission products have a characteristic kinetic energy. We therefore infer that this kinetic energy—the motion of the fission products—must have been acquired through some redistribution process within the original nuclear system. We therefore infer, following Bohr, that this redistribution of motion within the nuclear system is the result of a series of interactions, first between the nuclear system and the bombarding neutron, then between nearest-neighbor nucleons. We then represent this redistribution as a collective motion of the nuclear system, effectively averaging over the many individual interactions to produce the oscillations of the nuclear system. It is at this point that we represent this collective motion as an oscillation in the shape of the nucleus. Such a representation is good because the shape of the nucleus acts as an effective placeholder for the balance of processes within the nuclear system. E.g., when the nucleus has a "spherical" shape, the processes are perfectly balanced and therefore the system is stable. However, when the nucleus has an "oblong" shape, the processes are *imbalanced*, and the system is unstable. By describing fission as the result of oscillations in this shape from spherical to oblong, we thereby show how the nuclear system dynamically reaches the point of instability at which fission occurs.

Crucially, the shape of the nucleus is acting as a placeholder term in this explanation. Namely, it is a placeholder for the balance of many sub-nuclear interactions and motions. When we want to describe these interactions and motions in aggregate, shape becomes a relevant feature of the system. However, "shape" is only relevant when it itself is dynamic. I.e., even when we are making use of "shape" in our explanations, we are implicitly referring to the underlying interactions and motions of the nuclear system.

Moreover, the shape is only ever inferred, never observed. Rather, what we observe is the dynamic change of the nuclear system from stable to unstable that results from our dynamic intervention. Since we *already* associated the shape of the system with the stability produced by balanced internal interactions, we describe this dynamic change from a stable to unstable nuclear system in terms of the shape of the system.

[3.1.2]: Internal Energy Structure

We turn next to the explanation of the internal energy structure of the nucleus provided by the shell model. Again, this explanation is rather simple, and quite obviously processual: the energy structure of the nucleus is the result of the interaction of single nucleons with the aggregate potential created by the remainder of the nuclear system. This interaction can be further divided into an electromagnetic, chromodynamic, and spin interaction. Thus, the available energies of a nucleon in the nucleus are defined by these three interactions that nucleon can have with the nuclear potential. It should come as no surprise, at this point, that the bound state energies that these interactions produce are the result of balancing these three interactions. I.e., the relative strengths of the three interactions define a series of stable states in which the three interactions are balanced. There being multiple ways to balance these interactions, there are correspondingly many ways in which the nucleon can occupy a stable energy level.

Again, it is far more interesting to see how and why this energy structure appears as a feature of the nucleus in the first place. As already noted, the shell model of the nucleus is motivated by a qualitative analysis of patterns of naturally occurring stable isotopes, their spectral line signatures, and the decay of non-magic number isotopes into magic number isotopes. Quantitatively, the stability of magic-number nuclei is the result of a difference between the binding energies of isotopes with a magic number of nucleons and nuclei with one additional proton or neutron.

This energy difference manifests in various observed decay and spectral emission processes. Lighter nuclei with one more nucleon than a magic number tend to decay through nucleon emission and alpha decay (Mayer and Jensen 1955, 21). For example, Helium-5 and Lithium-5 will both α-decay into an α-particle and the additional neutron or proton respectively. Heavier nuclei will instead tend to β-decay into more stable isotopes.

Mathematically, we represent these decay and spectral emission processes as the result of changes in the energy of individual nucleons. These changes are in turn represented by jumps between energy levels defined by the interaction of the nucleon with the chromo-electrodynamic potential created by the rest of the nuclear system. I.e., nucleons jump between energy levels quantized according to figure 3 above.

This means that the energy structure is apparently playing an explanatory role in our explanations of decay and spectral emission processes. However, just as with the shape of the nucleus, the energy structure of the nuclear system is only acting as a means of identifying the relevant processes in the system. Recall that the goal of the shell model is to explain decay and spectral emission processes. It was for this reason that we constructed energy states. We first intervene on the nuclear system by, e.g., bombarding it with light. This produces a change in the system, namely the emission of line spectra. We then infer that our intervention must have produced, through a series of dynamics within the system, this emission of line spectra. We infer that it is single nucleons that are excited by this light, and which, in losing this excitation energy, emit the line spectra we observe. We know from the frequencies of the line spectra the energy of each emission, and therefore the energy of each energy excitation in a single nucleon. We therefore *construct* a collection of energy states that can exhibit these energy excitations, i.e., by ensuring that the energy of each possible excitation is equal to the difference in energy between two energy states. Importantly, we *choose* the mathematical potential in which we define these energy states. While we know the interactions that define this potential (chromodynamic, electromagnetic, and spin interactions), we do not know their relative strengths or balance within the nuclear system. This is something we must do entirely based on fitting our model to the observed energies of spectral emission (and decay).

In short, the energy structure is superfluous to our explanations of decay and spectral emission. Our interest is only in the balance of interactions between nucleons, and the interaction of, e.g., radiation with this balance that produces the absorption, excitation, and spectral emission processes we observe. I.e., not only do we define the energy structure of the nuclear system in terms of three interactions and their balance, we only ever make use of this energy structure in our explanations as a pragmatic means of identifying the relevant and explanatory processes.

[3.1.3]: Robust Processes in Formal Feature Explanations

Manifestly, both the liquid drop and shell models of the nucleus contain reference to exactly the same processes: chromodynamic interaction, an attractive force, and electromagnetic interaction, a repulsive force. Thus, manifestly, these two interactions are robust features of the models. If we only reify these two interactions, i.e., the processes in each model, the models will not be contradictory.

Each model constructs its token, explanatory processes out of these basic interactions. For example, in the liquid drop model, the difference between surface and volume chromodynamic interactions is the result of the difference in number of nearest-neighbor chromodynamic interactions that take place at the surface and within the volume of the system. This difference gives rise to two sorts of aggregate interaction, the surface-attractive interaction and the volume-attractive interaction. Similarly, the field interactions for individual nucleons within the shell model are the result of aggregating all of the chromodynamic and electromagnetic interactions of the other nucleons with the one in which we are interested.

Nevertheless, one might still be troubled that the two models disagree on empirical results. Even if they both refer to the same processes, they cannot both be correct in every empirical context. My contention, and what I show below, is that the difference between the models rests on their emphasis on how many and which processes to consider relevant, and which ones can be neglected in specific empirical instances. Neither model denies or contradicts the existence of the neglected processes. Quite the opposite: both models include explicit reference to the processes they are neglecting. However, both neglect certain processes precisely because they are not always relevant to the behavior being explained by the model. This being the case, I show here that the models do indeed become fully compatible precisely because neither is interested in being universally applicable.

The key to understanding this is that the liquid drop and shell models do not posit processes in a vacuum, without context.[18] Rather, the processes of both models only exist insofar as they are connected to specific interventions and dynamic alterations of the system. Thus, the processes posited by each model, themselves not directly observable as is, e.g., the emission of spectral lines, are contextualized to these interventions and dynamic alterations.

Let us consider again the shape of the nucleus. My contention here is that the nucleus only has a shape insofar as we interact with the nucleus in a particular way. In performing scattering experiments, we discover that there is a typical deflection pattern of our scattering probes. In collecting this information through many scattering trials, we can summarize it by claiming that the nucleus has a contained charge density that is responsible for the scattering. I.e., the nucleus has a shape. However, this shape is no more than a representation of the many individual deflections of scattering probes, the many interactions of the probe with the nuclear system. These deflections, then, do not involve the processes of, e.g., spin interaction described by the shell model. Instead, the interactions of the nucleons described by the liquid drop model are the processes that are relevant to the scattering and subsequent deflection processes.

The processes of the liquid drop model therefore do not deny those of the shell model. Rather, the liquid drop model recognizes that those processes are not relevant to the processes that define, and in which we determine, the shape of the nucleus. In the process of fission, and the processes of energy redistribution that make up the intermediate dynamics of fission, only nearest-neighbor interactions are relevant. Interactions between distant nucleons still occur. However, they are of a size that is negligible in the redistribution of energy within the nucleus.

---

[18] See Jungerman (2003) for a brief discussion of the importance of interconnectedness both in physical models and process ontology. Process philosophy, especially as advocated within Eastern philosophical circles

This is because the redistribution of energy in the nucleus fundamentally relies on single nucleons translating their energy to others directly (hence the term "collision" in Bohr's explanations). In contrast, distant-nucleon interactions become highly relevant when considering the excitation processes of a single nucleon. For this reason, the shell model includes these distant-nucleon interactions as important features. Importantly, the shell model does not treat these distant-nucleon interactions as any different in strength or variety from the ones that the liquid drop model neglects. They are the same processes in both models. The difference is that the shell model considers them relevant parts of the dynamics of decay and spectral emission, whereas the liquid drop model recognizes them as small enough to neglect for the purposes of mathematical simplicity.[19]

This, then, is how we explain the difference in empirical predictions between the two models. The two models have different explanatory aims. Namely, they are attempting to describe and explain (in terms of specific processes!) different dynamic phenomena. This difference in aim translates into the incorporation of different processes as relevant aspects of the intermediate dynamics of the nuclear system. Spectral emission, nuclear decay, and fission simply involve different sequences of dynamics, just as we learn about each through different interventions and different acts of observation. Nevertheless, both models consider the nuclear system to be composed of electromagnetic and chromodynamic interactions, and of all the multifarious combinations of these basic interactions that one could reasonably construct. Thus,

---

[19] Notice that as the number of nucleons increases, the importance of the asymmetry and pairing terms in the Weizsäcker equation becomes more important (see figure 2, the asymmetry energy). Something similar happens with the shell-correction terms in this equation. Thus, for larger nuclei, it becomes relevant to reincorporate the non-nearest-neighbor interactions into the model in order to explain nuclear shape. This is a further indication that the liquid drop model is not contradicting the shell model in its process terms. Far from it; the liquid drop model is affirming the dynamic ontology of the shell model.

process realism about the liquid drop and shell models produces a consistent, monist, realist interpretation of the models.

This is the explanatory defeat of things. Notice that the formal features of table 2 are exactly those features of the nuclear system that the thing realist would expect us to explain using the liquid drop and shell models. These explanations, as I have argued, are performed entirely in terms of processes: it is the processes of chromodynamic and electromagnetic interaction that explain the shape of the nucleus and the internal energy structure of the nucleus. In contrast, the supposed material features of the nucleus are those entities the thing realist would have us reify in order to explain the formal features. In short, the thing realist must argue that the explanations of formal features of the nucleus (and more importantly, the dynamics of fission and spectral emission and the like) require these material features in order to underlie the processes that are actually doing the explanatory work. I.e., the thing realist must offer an underlier argument that processes require things *ontologically*.[20]

[3.2]: Material Features of the Nucleus

We turn now to material features of the nucleus: the composition of the nucleus in terms of nucleons. Prima facie, the liquid drop and shell models of the nucleus agree on these features. Both models, after all, refer to nucleons in their explanations of nuclear behaviors. So, prima facie, the thing realist seems to have an available interpretational move: the nucleus is a system composed of smaller things. While the formal features of the nucleus are (collections of) processes, are explained by processes, and are used in the models to explain processes, the

---

[20] See Penn ("Processes Underlie Processes" manuscript) for a categorization of such arguments. The first explicit underlier argument was probably offered by Aristotle in *Physics* 1.2, 184b15–16.

nucleons may yet act as some sort of thing-underlier for nuclear processes. The contention is both an ontological and explanatory claim:

(Ontic Underlier Claim): Processes cannot exist without vehicles to undergo them. For example, a nuclear interaction presupposes that there are two things interacting.

(Explanatory Underlier Claim): Processes cannot explain without things. For example, any explanation involving a change in the nuclear system, like nuclear resonance oscillations, requires that there is a thing that changes in order to explain the change itself.

There are three problems with this move, discussed in turn.

[3.2.1]: Nucleons Qua Things Do No Explanatory Work

First we have already seen that it is the nuclear processes that are doing explanatory work. Therefore, nucleons are only explanatory insofar as they participate in these processes: it is only the dynamics of nucleons that are explanatory.[21] To suppose further that these dynamics deserve their own explanations is legitimate. However, it is illegitimate to suppose that these further explanations must involve things. The nucleon, just like the nucleus, is an experimental system with features to be explained, in particular a set of dynamics to be explained. Just like the explanations of nuclear features and behaviors above, we should suppose that the dynamics of nucleons, the behaviors of these nucleon systems, will be (and are in fact) explained by further processes, not things.[22]

---

[21] This point is made more thoroughly in Penn ("The Processes of the Candle Flame" manuscript).

[22] I will not discuss this further, since it is beyond the scope of this work. However, notice that nucleon dynamics and formal properties were explained from the beginning in terms of exchange interactions. This is the heart of Heisenberg's 1932(a, b, c) work on the nucleus (see especially 1932a). While Heisenberg's theoretical framework was rejected, the idea of nucleons being fluctuations of oscillations in the energy of an exchange force was taken up

[3.2.2]: The Underliers of Nucleon Dynamics Are Processes, Not Things

The thing realist must therefore rely on the ontological underlier claim. This leads us to our second problem. Specifically, any argument that is meant to support the existence of a thing-nucleon is equally an argument for the existence of a process-nucleon. I.e., any argument that there is a thing, "the nucleon," to underlie nuclear processes fails, or fails to rule out that this underlier is itself a process. This failure is the result of a general failure of such arguments: they rest on first recognizing that there is some stability in a system, and then claiming that this stability entails the existence of something static. For more, see Penn ("Processes Underlie Processes" manuscript).

In the particular case of the nucleon, we do not need any general failure of underlier arguments to see that the nucleon is itself a collection of further processes. Nucleons are at best atypical things. Our nuclear models, as well as models of these particles in field theory, already suggest that these supposed things do not possess characteristics like any thing we have discussed so far. Nucleons are non-local, non-localizable entities. They appear as fluctuations within an infinite field. Mathematically, they appear as creation and annihilation operators, mathematical entities that are typically associated with actions performed on and activities of a system, not objects within the system.

To see this, let us take the most basic feature of nucleons and see if they bear thing-realist interpretation. That is, consider the simple and basic property that nucleons come in two forms: protons and neutrons. These two things play quite similar roles in both the liquid drop and shell

---

by Yukawa (1935) in order to describe cosmic rays, and later reintegrated into the shell model of the nucleus. Moreover, the nucleons are now described field theoretically as the balanced and stable interaction of triplets of quarks, which are in turn described as fluctuations in the energy of a quark field.

models of the nucleus. Both engage in the same excitation processes, both engage in "collisions" that redistribute kinetic energy throughout the nucleus, both engage in collective motions as in fission, etc. In light of this, one may argue that protons and neutrons are not differentiated by their behaviors (their dynamics, the processes they undergo). Rather, one might suggest that the haeccity of protons and neutrons, or at least their "essential" properties of charge, mass, and spin, are the means by which we differentiate them. I.e., the thing realist might argue that neutrons and protons undergo the same processes (spin, excitation, collision, etc.), and yet are different entities. What differentiates them, then, must be non-processual. Hence, protons and neutrons, in virtue of being identifiably different, are things, not processes.

The point is well made, and is tempting. However, we cannot accept this line. Protons and Neutrons do not undergo the same processes. Undoubtedly, many of the processes we associate with neutrons in the nucleus are similar to those processes of protons. However, we also always associate with protons an electromagnetic interaction of a strength on the order of the electron charge that we do not associate with neutrons. The proton and the neutron undergo different internal chromodynamics—different quark interactions. In turn, these quarks undergo different Higgs interactions with different relative strengths. These different interaction strengths are used as the definition of the different quark masses, and by extension, the different masses of the proton and neutron. Protons and Neutrons undergo different decay processes, even within larger-scale models of the nucleus like the shell model. Neutrons can beta decay into a proton, an electron antineutrino, and an electron. Protons, however, beta decay into a neutron, a positron, and an electron neutrino. Protons and Neutrons are therefore defined both by different processes and similar processes of different strengths. They are therefore differentiated, by definition, in mathematical description, and by experiment, through differences of dynamics, not by static properties.

This leads us to our first counterclaim against the ontic underlier claim: processes, not things, underlie processes. For any nuclear processes for which the thing realist supposes that we should include a thing underlier, "the nucleon," we need only replace the thing term with the relevant process underlier. For example, the underlier of nucleon-nucleon interaction in the liquid drop model is the more-stable quark-quark interactions that define neutrons and protons. The underliers of beta decay processes of the nucleus in the shell model are the two different beta decay processes associated with independent neutrons and protons. And so on. Provided the processual underlier is more stable than the process it is meant to underlie, the processual underlier is perfectly capable of acting as an underlier. Things are unnecessary.

[3.2.3]: Things Inherit Incompatibility

However, the situation for thing-nucleons is far worse than simple impotence. In fact, if nucleons are treated as things with thing-like properties, they will inevitably inherit all of the incompatibility of the models in which they appear. This means that, even were we to suppose that the nucleus is composed of things (nucleons), we would still be left in the position in which we began our discussion: with two sets of incompatible thing-components suited for successful explanations of physical phenomena in different contexts.

To see how nucleons inherit incompatibility from nuclear models, we need look no further than the claims of energy structure within the nucleus. The liquid drop model consists of no internal energy structure. The shell model consists of rich internal energy structure. Now, supposing that nucleons are things with static properties and relations to other things, we notice that nucleons in the shell model must bear relations to other nucleons that are not born by the nucleons of the liquid drop model. In particular, shell-model-nucleons must bear the relations that compose the differences in energy of the various shells. This means that the nucleons of the liquid drop model, which do not bear these relations, are incompatible with the nucleons of the shell model. This same pattern can be demonstrated for properties like "being a surface nucleon," "having a nuclear energy state," and other monadic properties, in addition to relations.

We might suppose that nucleons are not defined essentially in terms of these incompatible relations or monadic properties. This at least removes the incompatibility. However, if nucleons are not meant to be the bearers of properties and the relata for nuclear relations, then surely they are utterly impotent even within thing realism. Their only purpose is to satisfy some a priori assumption that the nucleus is composed of things. Such an assumption could hardly prove particularly informative, useful, or persuasive.

[3.3]: Reestablishing Compatibility

We can now collect what we have discussed into table 3, similar to table 1 showing the incompatibility of thing-interpretations of the liquid drop and shell models, to show that the models are compatible on a pure process ontology:

Model —>	Liquid Drop	Shell
Explanandum of the model:	Fission, Capturing, and Scattering Processes	Excitation/Decay Processes
Explanans offered by the model:	Aggregate motions of the nucleons, brought about by the nearest-neighbor interactions of the nucleons.	Interaction of a single nucleon with the field of aggregated interactions provided by all other

		nucleons (Shell Interactions)
What processes compose the explanans:	- Chromodynamic interactions - Electromagnetic interactions	- Chromodynamic interactions - Electromagnetic interactions

Table 3: A collection of the processes that appear in both models. These collections are identical, but are used in different ways to explain different ends.

Moreover, we can demonstrate this compatibility by locating in both models the processes contained in the other. As I have already discussed, the liquid drop model contains explicit reference to shell-interactions in the Weizsäcker mass-energy equation in the form of shell correction terms. In the majority of cases, these correction terms are unnecessary to include. Their effect on the binding energy of the nucleus, and therefore on the aggregate motions of the nucleus, is miniscule compared to the effect of nearest-neighbor interactions. However, for particularly large or small nuclei the shell correction terms become relevant. For small nuclei, this is because the shell interactions are on the same length scale as the nearest-neighbor interactions. Nearest-neighbor interactions are therefore significantly impacted by the small size and occupancy constraints on nucleons in their lower energy shells. For larger nuclei, this is because the source of shell interactions—the aggregation of all nucleons save one into a single Fermi field—is strong enough to noticeably perturb the nearest neighbor interactions that guide fission and other aggregate motions. Thus, while the liquid drop model has little to say about the form that these shell interactions take, the model still assumes that these interactions are occurring, and includes them as essential explanatory features when they become relevant to the modeler.

The same can be said of the shell model and nearest-neighbor interactions. The shell model is predicated on the fact that all nucleons in the nucleus are affecting the nucleon of interest. The potential well formed by the sum of all of these interactions is what defines the decay and excitation processes for a given nucleon by defining the available energy levels for that nucleon, its shells. As these interactions change, the experimenter making use of the shell model will need to alter the potential well in order to reflect these changes. In other words, the potential well is fine-tuned to reflect the specific nucleon-nucleon interactions, both nearest-neighbor and other, so that the experimenter may treat these individual interactions in aggregate.

In essence, both models refer directly to the same processes—chromodynamic and electrodynamic interactions—in their construction. Their difference lies in that they differently aggregate and select the processes that are relevant to their respective explanatory goals. While the shell model does not explain fission, it was never designed to do so. Since the shell model nowhere denies or contradicts the existence of those processes that *do* explain fission, we avoid the explanatory problem of the thing interpretation of nuclear models. Similarly, these models are each fine-tuned in different ways by the experimenter in order to reflect the specific experimental situation for which they are being used. The liquid drop model will never be fine-tuned to better reflect the spectral emissions of excited nucleons because it was never intended to explain these processes. Again, nowhere does the liquid drop model deny or contradict the processes that are used in the shell model to model spectral emission and beta decay. In short, nowhere do the ontologies of these two models differ. Rather, it is because this single, processual ontology is used for two different scientific explanations that we have two different models.

[4]: Conclusion and Prospectus

We have now seen, once more, that an apparent thing can be redescribed and explained in terms of processes. In the case of the nucleus, as opposed to the cases of the molecule and the candle flame, we have also discovered that the supposed thing underliers of these defining and explaining processes are only things if one stretches the definition. Protons, neutrons, and electrons are all dubiously things at all. They are non-local and non-localizable, and they are all defined as fluctuations in an infinite field. We therefore conclude that the nucleus is not a thing, but a collection of processes. We also suspect that this collection of processes will have no thing-underliers.

We saw a further benefit in the process realist account of the nucleus. That is, the explanatory processes of the nuclear system are robust and non-contradictory across nuclear models. This is in stark contrast to the thing interpretation of the nuclear models, which produced irredeemable contradictions between the models. The thing interpretation of the liquid drop and shell models produced two different nuclei with different and incompatible structures, properties, and even haeccity. In providing a non-contradictory interpretation of these models, the process realist once again goes beyond mere parity with thing realism. I.e., process realism is once again shown to be superior in its account of scientific models.

Finally, we must note that the key difference between process and thing ontologies, in the context of models of the nucleus at least, is that they characterize models as explaining fundamentally different sorts of features of the nuclear system. The thing interpretation of the liquid drop and shell models characterized these models as offering explanations of static properties, structures, and thing-components: the shape of the nucleus, the magic numbers, etc. This is evidently not the purpose of these models, both historically and in contemporary uses. The models are used to explain behaviors (i.e., processes) first. Insofar as the nuclear system has certain behaviors that we *describe* in terms of these static properties—e.g., the way we use the shape of the nucleus to characterize the stages of oscillation within the processes of fission—these static properties are still useful tools. However, they are not explanatory and must not be reified. Only the behaviors of the system are of interest to those that use the model.

The process interpretation reorients our analysis to describe these behaviors. We interpret the liquid drop and shell models as tools to explain fission and excitation/decay processes, just as they were originally intended historically. In so doing, the process interpretation also reorients our interpretation of these models to match the experimental use to which they are put. These models are not meant to be descriptions of the static being of the world, but rather are constructed to describe, at their most basic level, specific experiments. The liquid drop model is meant to describe fission, neutron scattering, and neutron capture in neutron bombardment experiments. The shell model is meant to describe nucleon excitation and decay resulting in spectral emission and nuclear decay processes in decay and spectral line experiments. Experiments are dynamic first and foremost. The experimenter acts on the system, and observes some change in the system that results from the dynamic sequence their intervention triggers. It is only natural, then, to expect that models meant to describe these experiments are about those system dynamics, those processes. Inference to anything else is unwarranted.

References:

Barnes, J., ed. (1984). *The Complete Works of Aristotle*, Volumes I and II, Princeton: Princeton University Press.

Bohr, Niels. (1936). "Neutron Capture and Nuclear Constitution." *Nature*. 137:344-348.

———(1937). "Transmutations of Atomic Nuclei." *Science* 86:161-165.

Bohr, Aage, and Ben Mottelson. (1969). *Nuclear Structure*. New York: Benjamin.

Boniolo, Giovanni, Carlo Petrovich, and Gualtiero Pisent. (2002). "Notes on the Philosophical Status of Nuclear Physics." *Foundations of Science* 7 (4): 425-452.

Caurier, Etienne, Gabriel Martínez-Pinedo, Frederic Nowacki, Alfredo Poves, and Andres Zuker. (2005). "The Shell Model as a Unified View of Nuclear Structure." *Reviews of Modern Physics* 77:427-488.

Chen, Ruey-Lin (2018). "Experimental Individuation: Creation and Presentation." In Otàvio Bueno, Ruey-Lin Chen, and Melinda Bonnie Fagan (eds.) *Individuation, Processes, and Scientific Practices*. New York: Oxford University Press.

Cook, Norman D. (2006). *Models of the Atomic Nucleus: Unification through a Lattice of Nucleons*. Berlin: Springer.

Dupré, John (2010). *Processes of Life: Essays in the Philosophy of Biology*. Oxford: Oxford University Press.

———(2018). "Processes, Organisms, Kinds, and the Invecitability of Pluralism." In Otàvio Bueno, Ruey-Lin Chen, and Melinda Bonnie Fagan (eds.) *Individuation, Processes, and Scientific Practices*. New York: Oxford University Press.

Earley, Joseph E. (2003). "Constraints on the Origin of Coherence in Far from Equilibrium Chemical Systems." In Tim Eastman and Hank Keeton (eds.) *Physics and Whitehead: Quanum Process and Experience*, State University of New York Press.

———(2008). "How Philosophy of Mind Needs Philosophy of Chemistry," preprint available on Philsci Archive, url: http://philsci-archive.pitt.edu/4031/

Finkelstein, David (1996). *Quantum Relativity: A Synthesis of the Ideas of Einstein and Heisenberg*. Berlin: Springer-Verlag.

———(2003). "Physical Process and Physical Law." In Tim Eastman and Hank Keeton (eds.) *Physics and Whitehead: Quanum Process and Experience*, State University of New York Press.

Frisch, Otto R. (1934). "Induced Radioactivity of Sodium and Phosphorus." *Nature* 133:721-722.

Gamow, George. (1929). "Über die Structur des Atomkernes." *Physikalische Zeitschrift* 30:717-20.

Griesemer, James (2018). "Individuation of Developmental Systems: A Reproducer Perspective." In Otàvio Bueno, Ruey-Lin Chen, and Melinda Bonnie Fagan (eds.) *Individuation, Processes, and Scientific Practices*. New York: Oxford University Press.

Guay, Alexander and Pradeu, Thomas (forthcoming). "Right Out of the Box: How to Situate Metaphysics of Science in Relation to Other Metaphysical Approaches." *Synthese* special issue: "New Metaphysics of Science" ed. Max Kistler.

Guay, Alexander and Sartenaer, Olivier (2018). "Emergent Quasiparticles: Or, How to Get a Rich Physics from a Sober Metaphysics." In Otàvio Bueno, Ruey-Lin Chen, and Melinda Bonnie Fagan (eds.) *Individuation, Processes, and Scientific Practices*. New York: Oxford University Press.

Heisenberg, Werner (1932a). Über den Bau der Atomkerne I. *Zeitschrift für Physik* 77:1-11.

———(1932b). Über den Bau der Atomkerne II. *Zeitschrift für Physik* 78:156-164.

———(1932c). Über den Bau der Atomkerne III. *Zeitschrift für Physik* 80:587-596.

Kaiser, Marie (2018). "Individuating Part-Whole Relations in the BIological World." In Otàvio Bueno, Ruey-Lin Chen, and Melinda Bonnie Fagan (eds.) *Individuation, Processes, and Scientific Practices*. New York: Oxford University Press.

Love, Alan C. (2018). "Individuation, Individuality, and Experimental Practice in Developmental Biology." In Otàvio Bueno, Ruey-Lin Chen, and Melinda Bonnie Fagan (eds.) *Individuation, Processes, and Scientific Practices*. New York: Oxford University Press.

Mayer, Maria G., and J. Hans D. Jensen. (1955). *Elementary Theory of Nuclear Shell Structure*. New York: Wiley.

Morrison, Margaret. (2011). "One Phenomenon, Many Models: Inconsistency and Complementarity." *Studies in History and Philosophy of Science* 42 (2): 342-351.

Meitner, Lise. (1936). "Künstliche Umwandlungsprozesse beim Uran." In Egon Bretscher (ed.), *Kernphysik: Vorträge gehalten am Physikalischen Institut der Eidgenössischen Technischen Hochschule Zürich im Sommer 1936 (30. Juni - 4. Juli)*. Berlin: Springer.

Meitner, Lise, and Otto R. Frisch. (1939). "Disintegration of Uranium by Neutrons: A New Type of Nuclear Reaction." *Nature* 143:239-40.

Pais, Abraham. (1991). *Niels Bohr's Times, In Physics, Philosophy, and Polity*. New York: Oxford University Press.

Pardeu, Thomas and Ferner, Adam (2018). "Ontologies of Living Beings: Introduction." *Philosophy,Theory, and Practice in Biology* 9:4.

Pemberton, John (2018). "Individuating Processes." In Otàvio Bueno, Ruey-Lin Chen, and Melinda Bonnie Fagan (eds.) *Individuation, Processes, and Scientific Practices*. New York: Oxford University Press.

Portides, Demetris. (2011). "Seeking Representations of Phenomena: Phenomenological Models." *Studies in History and Philosophy of Science* 42 (2): 334-341.

Seibt, Johanna (1990). *Towards Process Ontology: A Critical Study of Substance-Ontological Premises*, Ph.D. Thesis, University of Pittsburgh; UMI Microfiche Publication; available at the author's webpage.

———(2004). “Free Process Theory: Towards a Typology of Processes,” *Axiomathes*, 14(3): 23–57.

———(2005). *General Processes. A Study in Ontological Category Construction*, Habilitationsschrift, University of Konstanz, Germany, Archive Publication. Chapters 2 and 3 are republished as *Activities*, DeGruyter, forthcoming 2017.

———(2015). “Non-Transitive Parthood, Leveled Mereology, and the Representation of Emergent Parts of Processes.” *Grazer Philosophische Studien* 91: 165-190.

———(2016). “How to Naturalize Sensory Consciousness and Intentionality Within a Process Monism With Normativity Gradient: A Reading of Sellars.” In J. R. O’Shea (ed.) *Sellars and His Legacy* (187-221). Oxford: Oxford University Press.

———(2016). “Process Philosophy.” *Stanford Encyclopedia of Philosophy* (Winter 2016 edition). Edward N. Zalta (ed.) URL = <https://plato.stanford.edu/archives/win2016/entries/process-philosophy/>.

———(2018b). “What is A Process? Modes of Occurrence and Forms of Dynamicity in *General Process Theory*,” in R. Stout (ed.), *Processes, Experiences,and Actions*, Oxford: Oxford University Press, forthcoming.

Stuewer, Roger H. (1994). “The Origin of the Liquid-Drop Model and the Interpretation of Nuclear Fission.” *Perspectives on Science* 2:76-129.

Teller, Paul. (2004). “How We Dapple the World.” *Philosophy of Science* 71 (4): 425-447.

Weizsäcker, Carl Friedrich von. (1935). “Zur Theorie der Kernmassen.” *Zeitschrift für Physik* 96:431-458.

Wiggins, David (2016a). *Essays on Identity and Substance*. Oxford University Press UK.

———(2016b). Activity, Process, Continuant, Substance, Organism. *Philosophy* 91 (2):269-280.

———(2016c). *Continuants: Their Activity, Their Being, and Their Identity*. Oxford University Press.

Yukawa, H. (1935). On the Interaction of Elementary Particles, I. Physico-Mathematical Society of Japan, *Proceedings*, 17: 48-57.